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Experimental Tunnel-Diode Converter for Conversion of X-Band Frequencies to UHF

GUSTAV H. BLAESER

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ERRATA

Page 8, after Eq(13)

for $\dfrac{Z_g}{Z_0} = \tan$,   read $\dfrac{Z_g}{Z_0} \tanh$

for $l_1 = \dfrac{1.418 \times 1.8^O}{360^O} = 0.007$ in. read $l_1 = \dfrac{0.88 \times 1.8^O}{360^O} = 0.004$ in.

Last paragraph

for   In the case of $\lambda = 0.44$ in., the $3/4\lambda$ sections had a length of
of 0.66 in. and the $\lambda/2$ piece had a length of 0.708 in.

read   In the case of $\lambda = 0.88$ in., the $3/4\lambda$ sections had a length of
0.66 in. and the $\lambda/2$ piece had a length of 0.44 in.
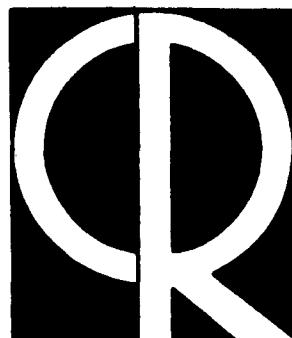
Research Report

Experimental Tunnel-Diode Converter for Conversion of X-Band Frequencies to UHF

GUSTAV H. BLAESER

Abstract

A tunnel-diode down converter designed and developed for conversion from X-band frequencies to UHF has proved that low noise figures are possible, when a forward bias voltage is chosen in the first region of the I-V characteristic of the tunnel diode so that the conductance G_o is positive. When a sufficient local-oscillator voltage can drive the operating point into the negative-resistance region, the tunnel diode down converter exhibits a conversion gain and a noise figure 3 to 4 db lower than attainable with converters having common diodes. With a local oscillator frequency of 8.33 kMcps and an IF of 30 Mcps, an average noise figure of 4.5 db was measured. For mismatched conditions of the input admittance, a generator conductance G_g of 2 mhos was advantageously chosen in order to get a low noise factor and high gain. A microstrip line transformer was used to establish the high generator conductance.

The measured noise figure of an improved second device, similar to the first one, was 3.0 db.

The experimental devices are of attractively small size.

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1. INTRODUCTION

As yet it has not been possible to convert a microwave-frequency signal to an
UHF signal with common mixer crystals while achieving low noise and high gain.
Down converters with this type of diode crystal have shown an average conversion
loss of 6 db. Other kinds of down converters such as parametric converters have
poor noise figures because of the involved ratio of input frequency to output
frequency.

The main feature of a tunnel-diode down converter is the low-noise conversion
of high-frequency signals with a substantial conversion gain at the same time.
Noise figures of tunnel-diode down converters, which are operated on the positive
resistance side and driven by a pump frequency over a maximum of current into the
negative resistance region, are usually 3 to 4 db better than those of any other mixer
diodes.

As far as frequencies are concerned, down converters with tunnel diodes have
been operated until now with frequency ratios of 2800 Mcps to 30 Mcps, and noise
figures of 3 to 4 db.

2. EQUIVALENT NOISE CONDUCTANCE G_e

The noise is the result of only the current flow through the tunnel diode, and is therefore a shot noise.

Since the nonlinearity of a resistance, rather than a reactance, is utilized for the conversion, involved frequency ratios are eliminated. The equivalent shot noise conductance is

$$G_e = \frac{e\,I_O}{2kT} \, ,$$

(1)

where

e = electronic charge = 1.6×10^{-19} coulombs

I_O = tunnel-diode current at dc bias

k = Boltzmann's constant = 1.38046×10^{-23} joules deg^{-1}

T = ambient temperature, 290°K

3. GENERATOR CONDUCTANCE G_g

In exhibiting a low noise figure an important factor is the generator conductance G_g [Figure 1 and Eq. (2)] which has to be large in order to make all the ratios with G_g in the noise figure Eq. (2) low.

$$F = 1 + \frac{T}{T_o}\left[\frac{G_e}{G_g} + \frac{G_1}{G_g} + \frac{G_L + G_2 + G_e}{G_g} \cdot \frac{\overline{G}_1}{\overline{G}_2} \cdot \frac{1}{1 - \frac{2\left(\sqrt{1+\overline{g}_c}-1\right)}{\overline{g}_c}}\right] .$$

(2)

In this equation

T = ambient temperature

T_o = reference temperature (290°K)

G_e = equivalent shot noise conductance of the tunnel diode

G_g = generator conductance

G_1 = loss conductance of the signal circuit

G_2 = loss conductance of the IF circuit

G_L = load conductance

$\overline{G}_1 = G_1 + G_g + G_o$

$\overline{G}_2 = G_2 + G_L + G_o$

G_o = linear conductance of the tunnel diode at bias point

$\bar{g}_c$ = normalized conversion gain = $\dfrac{4\lambda}{(1-\lambda)^2}$

$\lambda = \dfrac{\mathscr{G}^2 V_3^2}{G_1 G_2}$ = gain parameter

$\mathscr{G}$ = coefficient of nonlinearity

V_3 = voltage of the local oscillator frequency
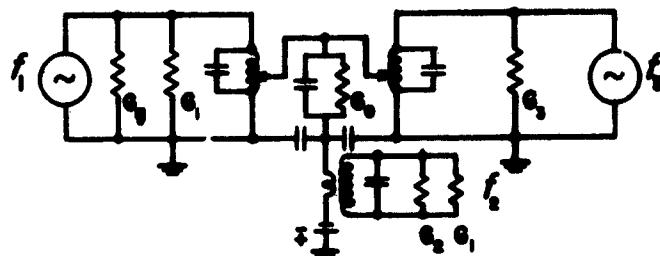
Figure 1. Schematic Diagram of the Tunnel Diode Converter Circuit

As K. K. N. Chang has pointed out,[1] low noise figures are possible with high gain when the generator conductance G_g is mismatched to the admittance of the input. In this case, the bandwidth will be small and the stability sensitive to changes. The stability can be improved by approaching matched conditions if one is willing to accept higher noise figures and lower conversion gain.,

4. CHOICE OF TUNNEL DIODE

For radiometers and other receiving devices where low noise is desirable, it would be helpful to know the lowest noise figure of a tunnel diode converter for converting X-band frequencies to 30 Mcps when the tunnel diode is operated on the positive resistance side in the first region near the peak current of the I-V characteristic (Figure 2). The particular X-band frequency was f_1 = 8.33 kMcps.

The tunnel diode chosen as best for this purpose was a Sylvania tunnel diode D 4168 D.

The characteristic values of this tunnel diode are

$-R_d$ = 59Ω

r_d = 1.5Ω

C = 1.2 $\mu\mu f$

L_d = 0.15×10⁻⁹ h

I_p = 2.4 ma

I_p/I_v = 7.75

f_{osc} = 10.02 kMcps

4
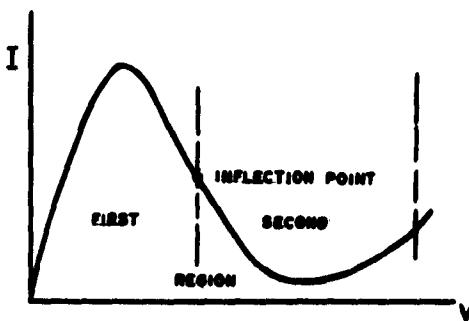
Figure 3. I-V Characteristic of a Tunnel Diode Divided into the First and Second Region

5. PROPER CHOICE OF GENERATOR CONDUCTANCE G_g

When an operating point at G_o on the positive resistance side of the first region of the I-V characteristic is chosen (Figure 3), the currents of the three frequencies are

$$I_1 = V_1 \overline{G}_1 - b V_2 V_3 ,$$

$$I_2 = V_2 \overline{G}_2 - b V_1 V_3 , \tag{3}$$

$$I_3 = V_3 \overline{G}_3 - b V_1 V_2 .$$

Setting the second equation in Eq. (3) equal to zero one finds

$$I_1 = V_1 \overline{G}_1 - \frac{b^2 V_3^2}{\overline{G}_2} V_1 ,$$

and if

$$\frac{b^2 V_3^2}{\overline{G}_1 \overline{G}_2} = \lambda, \text{ which is here the gain parameter,}$$

$$I_1 = V_1 \overline{G}_1 - \lambda \overline{G}_1 V_1$$

or

$$I_1 = V_1 \overline{G}_1 (1 - \lambda) . \tag{4}$$

There are two conditions one can establish, namely, matched and mismatched conditions.

Considering

$$Y_1 = \frac{I_1}{V_1} = \overline{G}_1 (1 - \lambda) , \tag{5}$$
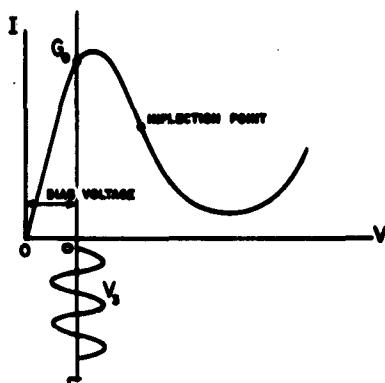
Figure 3. I-V Characteristic of the Tunnel Diode with Pump-Frequency Voltage V_3

which is the input admittance, then Y_1 is composed of the generator conductance G_g and G_{in}.

Thus

$$Y_1 = G_g + G_{in} \tag{6}$$

or

$$G_{in} = Y_1 - G_g . \tag{7}$$

It follows from Eqs. (5) and (7) that

$$G_{in} = \overline{G}_1 (1 - \lambda) - G_g = K_1 G_g . \tag{8}$$

If in Eq. (8) the coupling factor $K_1 = 1$,
then

$$G_{in} = G_g , \tag{9}$$

and matched conditions are established. For this condition, the bandwidth could be made wide but the gain would be low and the noise factor high. For this reason matched conditions are not used in the experimental device.

Further consideration of Eq. (8) shows that, if it is solved for G_g, then

$$G_g = G_0 \left(\frac{1 - \lambda}{K_1 + \lambda} \right) . \tag{10}$$

6

and if Eq. (10) is substituted into the noise factor Eq. (2)

$$F \gtrless 1 + \frac{1 + K_1}{(1 - \lambda)\lambda} \quad .$$

(11)

The noise factor will be minimum for $K_1 = 1$ and $\lambda = 0.5$. An evaluation of Eq. (11) gives

$$F \gtrless 1 + \frac{2}{(0.5)0.5} = 9 \text{ pr} = 9.5 \text{ db} ,$$

which is approximately the lowest possible noise factor for matched conditions.

But noise factors of 9.5 db can also be achieved for the same conversion with common diodes. With this type of diode the disadvantage will be the accompanying loss whereas the tunnel diode down converter operating under matched conditions shows a small conversion gain.

In order to achieve lower noise factors with tunnel diodes in the converter under consideration, it is necessary to establish mismatched conditions.

6. MISMATCHED CONDITIONS

To establish mismatched conditions, the coupling factor can be

$$-1 < K_1 < 0$$

and the gain parameter λ high.

With a chosen coupling factor $K_1 = -0.891$ and $\lambda = 0.89167$ one obtains

$$G_g = G_o \frac{1 - \lambda}{K_1 + \lambda} = 0.0125 \times 160 = 2 \text{ mhos} .$$

The high generator conductance $G_g = 2$ mhos, however, can only be achieved by means of a transformer between the much lower conventional conductance of the coupling waveguide G_w and G_g (Figure 4).

This transformation was realized by using a microstrip line[2,4] in which the tunnel diode was covered within a dielectric between a ground plate and a conductor representing a transformer.
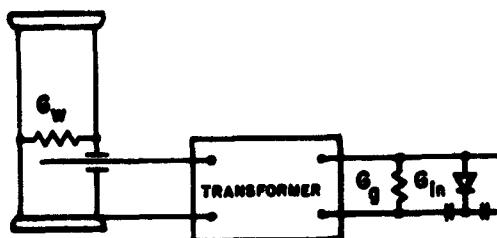
Figure 4. Schematic Circuit of Transformer for Conversion of G_w to G_g

7. MICROSTRIP LINE

In a test setup, the requirement of a transformer was satisfied by using a tapered conductor with three sections of 3/4 wavelength. The microstrip line was coupled to the waveguide piece using a probe. The dielectric material was 1/16 inch plexiglass with a dielectric constant $\epsilon = 2.6$. A variable plunger provided a short circuit between the ground plate and the conductor in order to establish the right conductance point (Figure 5). The ground plate was 2 inches wide.

Generally, the characteristic impedance can be determined by the equation

$$Z_0 = 377 \frac{h}{w} \sqrt{\frac{1}{\epsilon}} . \tag{12}$$

For instance, with $w_3 = 0.93$ in., $h = 0.0625$ in., and $\epsilon = 2.6$, then $Z_{0_3} = 15.7\Omega$.
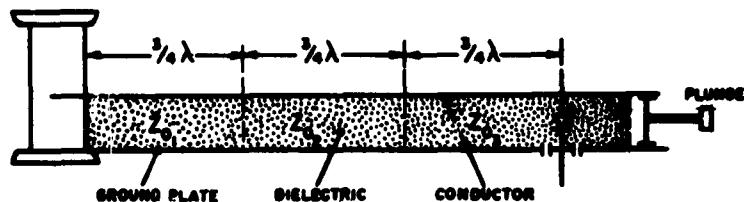
Figure 5. Microstrip Line with the Tunnel Diode at the End of the Third 3/4λ Transformer Section

In order to establish the right mismatched conditions the tunnel diode had to be placed at a distance l_1 from the short-circuit point (Figure 6) where the high generator conductance of 2 mhos, corresponding to the low generator impedance Z_g of 0.5 Ω, exists.
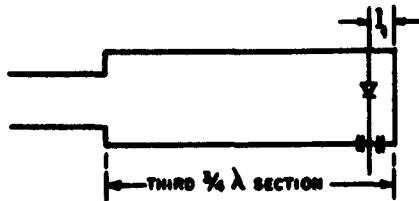
Figure 6. Third $3/4\lambda$ Section of Transformer with Tunnel Diode Near the End of the Line

Because

$$Z_g = jZ_0 \tan \frac{1_1}{\lambda} 360^0 , \tag{13}$$

it is

$$\frac{Z_g}{Z_0} = \tan \frac{1_1}{\lambda} 360^0 = 0.032 = 1.8^0 .$$

Then

$$1_1 = \frac{1.418 \times 1.8^0}{360^0} = 0.007 \text{ in.}$$

Obviously, this value is much smaller than the diameter of the tunnel diode itself, so that a proper adjustment near the short circuit is impossible.

The length 1_1 was made variable by means of a rotatable plunger which could provide a short circuit $\lambda/2$ away from the tunnel diode (Figure 7a). The second device with a similar transformer was so designed that the tunnel diode was at the $\lambda/4$ point of the third $3/4\lambda$ section (Figure 7b).

a)   b)
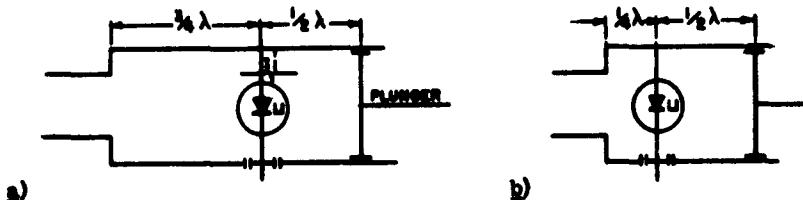
Figure 7. Third $3/4\lambda$ Section of Transformer with Tunnel Diode a) at the End of this Section and Plunger at the End of an Added $\lambda/2$ Section; b) at the $\lambda/4$ Point and Plunger at the End of the $3/4\lambda$ Section

In this way, it was possible to find a point at which the noise factor was a minimum. In the case of $\lambda = 0.44$ in., the $3/4\lambda$ sections had a length of 0.66 in. and the $\lambda/2$ piece had a length of 0.708 in. The different widths of the $3/4\lambda$ sections were $w_1 = 0.32$ in., $w_2 = 0.38$in., and $w_3 = 0.93$ in., and the respective characteristic impedances $Z_{0_1} = 61\Omega$, $Z_{0_2} = 38.2\Omega$, and $Z_{0_3} = 15.7\Omega$.

8. TEST SETUP

The whole tunnel-diode down converter has been designed to a space of 5 1/2 by 2 in. but could have been shortened in length by using $\lambda/4$ transformers. In comparison, a balanced down converter with normal crystals for X-band frequencies occupied an area of about 14 by 7 in.

The tunnel diode down converter is shown in five photographs. The first photograph shows the front view where the converter is mounted on a piece of X-band waveguide. Note especially in the second photograph the adapter for IF output. Then a perspective view of the converter shows the hole in the piece of waveguide where the coupling probe of the transformer is injected. The last two photographs show the converter with other instruments used to measure the noise figure.

9. IF OUTPUT

Success in reaching good noise figures and operating at X-band frequencies lies to a great extent in the proper design of the inner insulated pin of the adapter. Its tapered head has to provide the lowest possible parallel capacitance to the diode. The adapter also provides series capacitance to ground to short circuit RF. Figure 12 shows in enlarged form the arrangement used in the experimental device.

The 30 Mcps IF was filtered out by an IF preamplifier with a noise figure of 2 db.

10. CALCULATION OF NOISE FIGURE

The linear conductance G_o was chosen at a dc bias point where $R_d = 80$ ohms. Now for calculating the noise figure we have:

$G_e = 20 \times I_o = 0.039$ mho $\qquad G_o = 0.0125$ mho

$G_g = 2$ mhos $\qquad G_L = 0.02$ mho

$\overline{G}_1 = G_g + G_o = 2.0125$ mhos $\qquad \overline{G}_2 = G_L + G_o = 0.0325$ mho

$K_1 = -0.891$ $\qquad \lambda = 0.89167$

Then the normalized conversion gain is

$$\overline{g}_c = \frac{4\lambda}{(1-\lambda)^2} = 304 \text{ pr.}$$
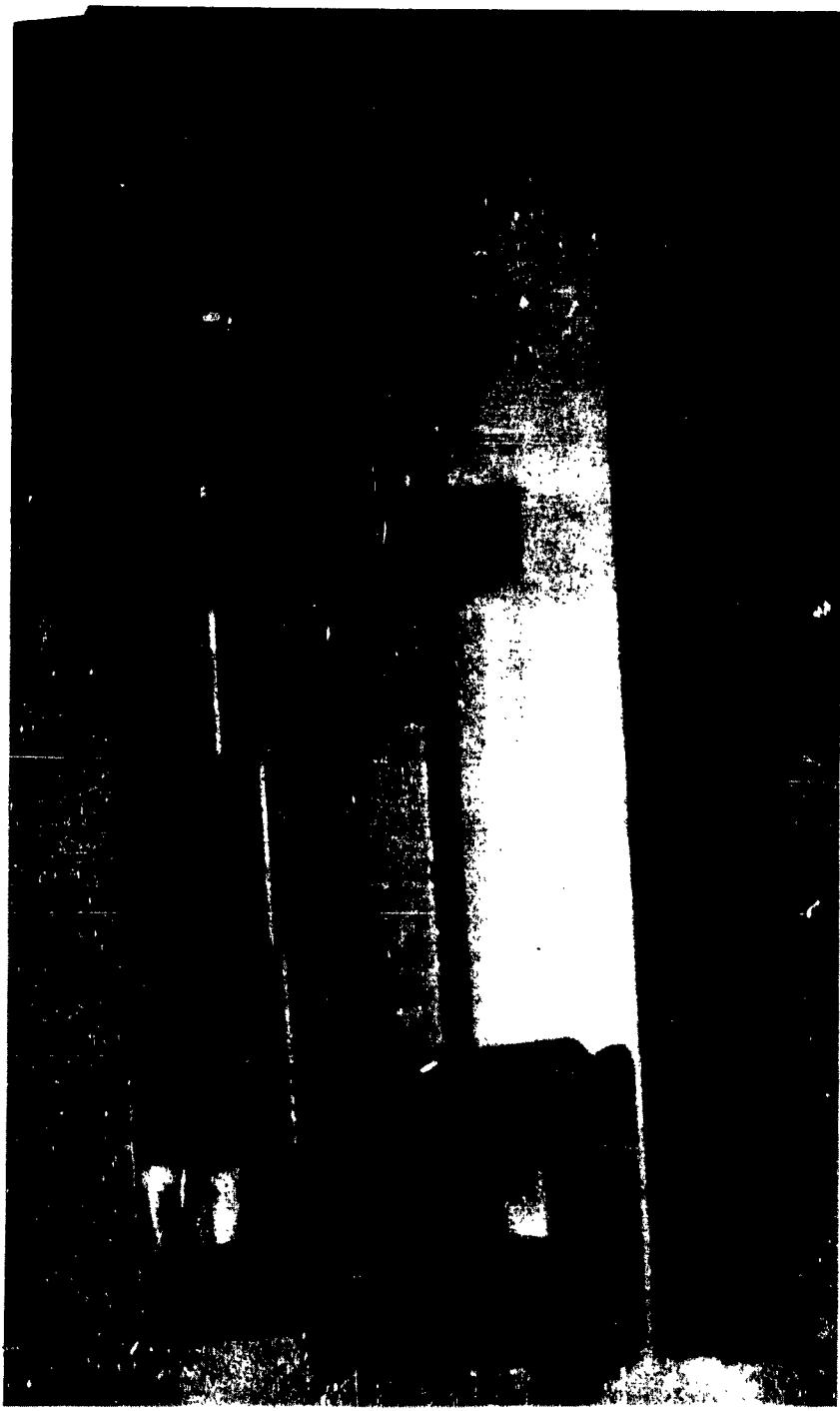
Figure 8. Front View of Microstrip Line of the Tunnel-Diode Down Converter Mounted on a Piece of Waveguide for X-Band Frequencies
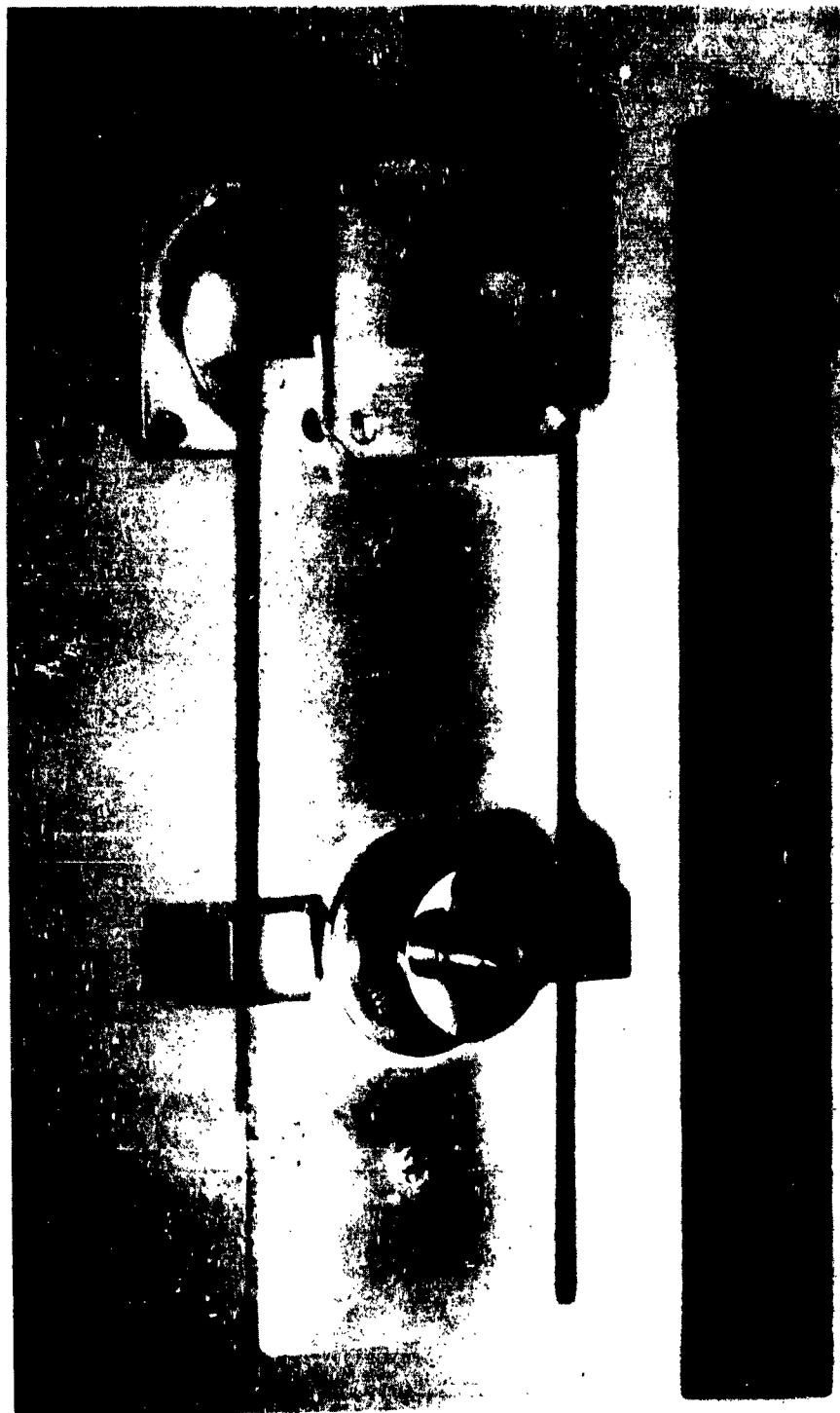
Figure 9. Back View of Tunnel-Diode Down Converter with Adapter for IF Output

Figure 10. Perspective View of Tunnel-Diode Down Converter
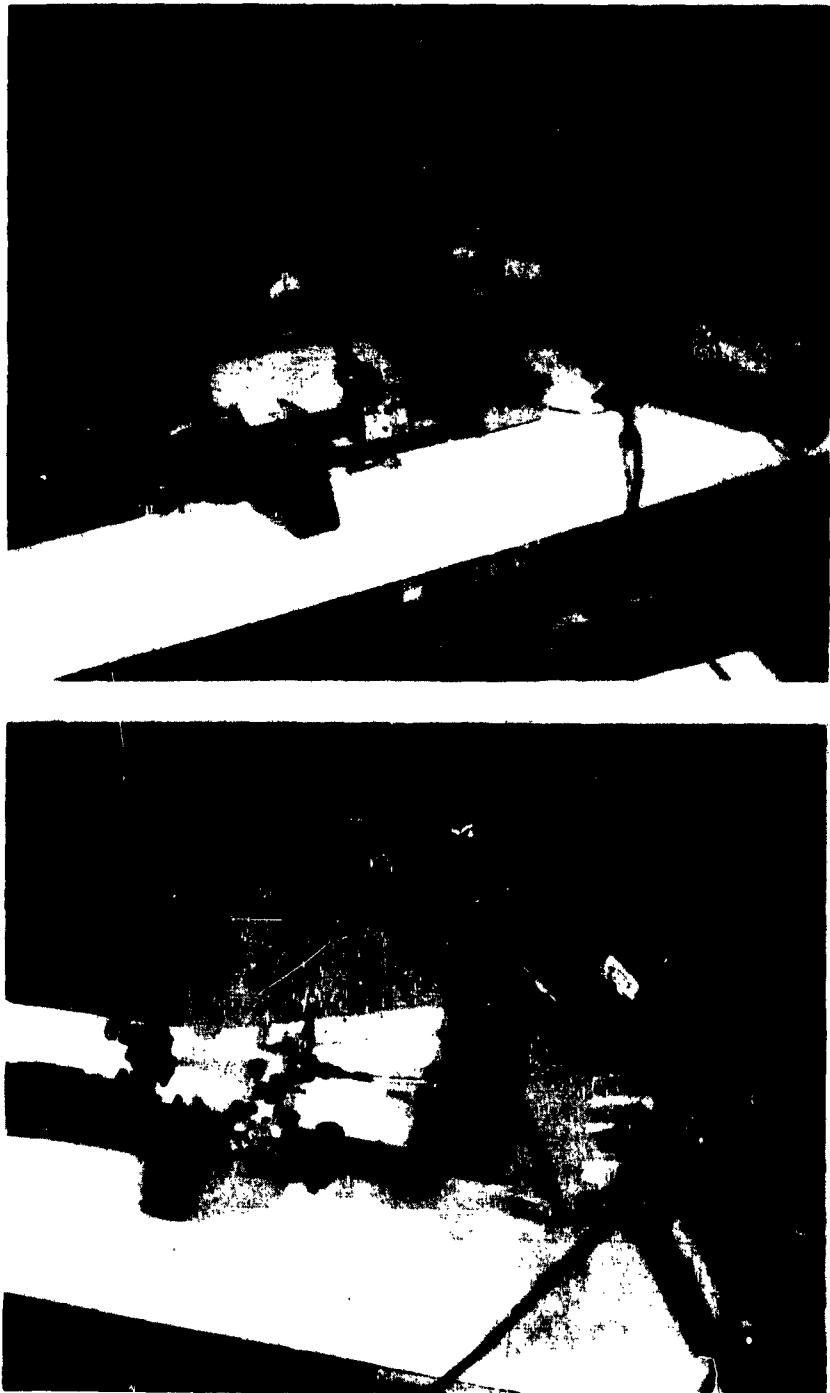
Figure 11. Test Setup on Bench
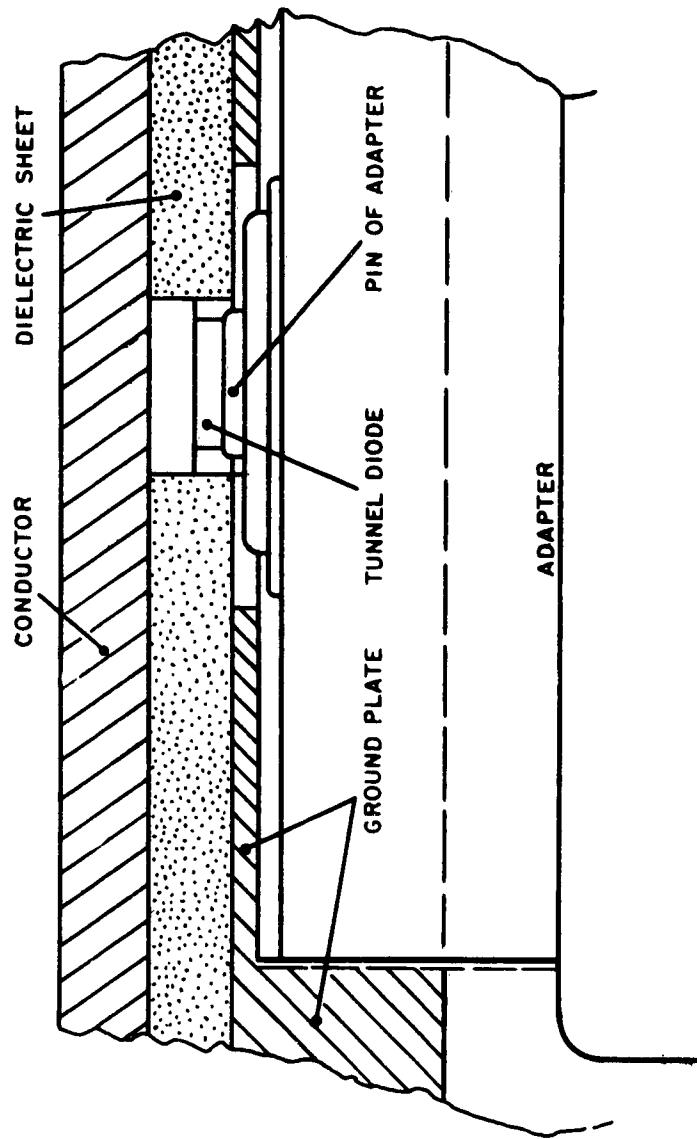
Figure 12. Enlarged Drawing of Arrangement of Conductor, Dielectric Sheet, Tunnel Diode, and Ground Plate with Adapter for IF Output

The other values in the noise factor Eq. (2) are

$$\frac{G_e}{G_g} = \frac{0.039}{2} = 0.0195 ,$$

$$\frac{G_L + G_e}{G_g} = \frac{0.059}{2} = 0.029 ,$$

$$\frac{\overline{G}_1}{\overline{G}_2} = \frac{2.0125}{0.0325} = 62 , \quad \text{and} \quad \frac{1}{1 - \frac{2\left(\sqrt{\overline{g}_c + 1} - 1\right)}{\overline{g}_c}} = 1.1 .$$

Substituting these values in to the noise figure Eq. (2) and assuming that G_1 and G_2 are zero with $\frac{T}{T_0} = 1$, the noise figure is

$$F = 1 + \left[0.0195 + 0.029 \times 62 \times 1.1\right] = 2.997 \text{ pr} = 4.8 \text{ db}.$$

11. CALCULATION OF BANDWIDTH

The calculation of the bandwidth can be followed from the assumption that G_1 and G_2 are also equal to zero. The bandwidth is $2\Delta f_1 = B_1 f_1$.

The relative bandwidth $B_1 = \dfrac{1}{\sqrt{\overline{g}_c} (1 + c) \overline{Q}_1}$. $\qquad(14)$

Known are

$$\omega_1 = 52.3 \times 10^9 \text{cps} \qquad \omega_2 = 188.4 \times 10^6 \text{cps}$$
$$C_1 = 1.6 \ \mu\mu f \qquad C_2 = 100 \ \mu\mu f$$
$$\overline{G}_1 = 2.0125 \text{ mhos} \qquad \overline{G}_2 = 0.0325 \text{ mhos}$$
$$\qquad\qquad\qquad\qquad \overline{g}_c = 304 \text{ pr}$$

Then

$$\overline{Q}_1 = \frac{\omega_1 C_1}{\overline{G}_1} = 0.041$$

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$$\overline{Q}_2 = \frac{\omega_2 C_2}{G_2} = 0.57$$

$$c = \frac{\overline{Q}_2 \omega_1}{\overline{Q}_1 \omega_2} = 3878$$

$$B_1 = \frac{1}{17.4 \times 3879 \times 0.041} = 0.000361 \ .$$

Therefore the bandwidth

$$B_1 f_1 = 0.000361 \times 8.33 \times 10^9 = 3 \ \text{Mcps} \ .$$

12. CONVERSION GAIN

The conversion gain can be calculated from the equation

$$\overline{g}_c = \frac{Q_g Q_L}{\overline{Q}_1 \overline{Q}_2} g_c \ , \tag{15}$$

where

$$Q_g = \frac{\omega_1 C_1}{G_g} = \frac{0.0837}{2} = 0.0418 \quad \text{and} \quad Q_L = \frac{\omega_2 C_2}{G_L} = \frac{0.01884}{0.02} = 0.942 \ .$$

Then

$$g_c = 304 \ \frac{0.041 \times 0.57}{0.0418 \times 0.942} = 191 \ \text{pr} = 22.8 \ \text{db} \ .$$

13. NOISE FIGURE MEASUREMENT

In the first device two D4168D tunnel diodes were tested for a noise figure measurement (Figure 13). Each diode gave a noise figure of 4.5 db.

The total noise figure is

$$F = F_1 + \frac{(F_2 - 1)}{g_c} \ . \tag{16}$$
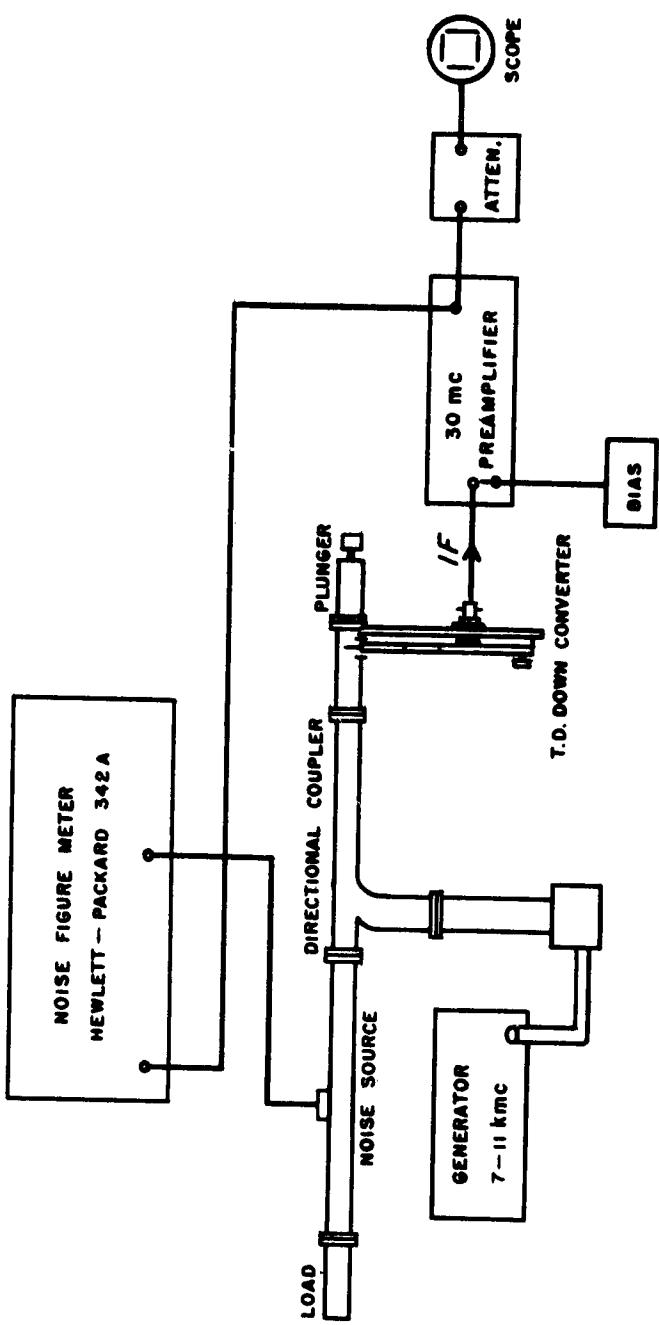
Figure 13. Schematic Test Setup for Noise Figure Measurement

where

F_1 = noise figure of the tunnel-diode down converter,

F_2 = noise figure of the preamplifier (2 db = 1.585 pr),

g_c = conversion gain of the tunnel-diode down converter.

Then

$$F_1 = F - \frac{(F_2 - 1)}{g_c} = 2.818 - \frac{1.585 - 1}{191}$$

$$= 2.818 - 0.003 = 2.815 \text{ pr}$$

$$= F_1 = 4.5 \text{ db}.$$

The noise figure of the tunnel-diode down converter differs very little from the total noise figure because of the high conversion gain. The stability of the down converter for F_1 = 4.5 db was very good while lower noise figures of 3.5 db gave rise to instability. Then the bandwidth is much smaller. When the down converter breaks into oscillations the bandwidth becomes zero. The combination of bandwidth, gain, and noise figure give a measure of stability. The noise figure of the improved second device was 3.0 db.

14. TUNNEL-DIODE DEGRADATION

Testing the first device of the converter it was discovered that both Sylvania D4168D tunnel diodes, which are germanium diodes, changed their electrical characteristics after daily operation of a few hours over a week until they finally lost their tunneling property. A report from RCA about degradation[3] on gallium-arsenide tunnel diodes notes that a change in electrical characteristics occurs when operated in the forward injection-current region. The presence of copper impurities that act as recombination centers and result in degradation has been found in such gallium-arsenide tunnel diodes. Therefore, it is conceivable that quite a similar effect of degradation has taken place on those two D4168D germanium tunnel diodes tested as down converters. The third D4168D tunnel diode tested in the improved device did not show such degradation effects.

15. CONCLUSION

The information given in this report can only be considered as a narrow introduction to a broad subject. It has been shown that low noise figures of 4.5 db and recently 3.0 db are possible when converting X-band frequencies in

tunnel-diode converters to 30 Mcps while also obtaining a conversion gain. There seems to be the possibility of achieving similar values of low noise figure for K-band conversion by tunnel diodes with adequate higher self-resonant frequencies. A possible restriction of bandwidth could be avoided by using cascade circuits which could increase the bandwidth in the first stage about 8 percent.

It is to be expected that the degradation of tunnel diodes, operated in the injection current region, might be reduced in the near future.

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Mass. Electronics Research Directorate
EXPERIMENTAL TUNNEL-DIODE CONVERTER
FOR CONVERSION OF X-BAND FREQUENCIES TO
UHF by G. H. Blaeser. December 1962.
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oped for conversion from X-band frequencies to
UHF has proved that low noise figures are possible,
when a forward bias voltage is chosen in the first
region of the FV characteristic of the tunnel diode so
that the conductance G_o is positive. When a suffi-
cient local-oscillator voltage can drive the operating
point into the negative-resistance region, the tunnel
diode down converter exhibits a conversion gain and
a noise figure 3 to 4 db lower than attainable with
converters having common diodes. With a local os-
cillator frequency of 8.33 kMcps and an IF of 30
Mcps, an average noise figure of 4.5 db was meas-
ured. For mismatched conditions of the input admit-
tance, a generator conductance G_g of 2 mhos was
advantageously chosen in order to get a low (over)